LOSS OF CONTAINMENT: EXPERIMENTAL VALIDATION OF INITIALLY SUBCOOLED TWO-PHASE CRITICAL FLOW MODELS

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Abstract:

A new setup allows us to experiment initially subcooled two-phase critical flows with five different fluids: water, R11, methanol ethyl acetate and butane. We verify that good estimates of the mass flow rate can be derived from the extended HEM for all of the fluids in high subcooling conditions (within ±20% accuracy). In low subcooling conditions, a satisfactory agreement (±30% accuracy) with the DEM or HEM predictions is found. This means that the main phenomena involved seem to be correctly taken into account.

Scope and aims:

Safety studies (Seveso directive) leed companies to estimate the ultimate consequences of loss of containment events. In the case of a tank containing a pressurized liquid this means that it is essential to evaluate the two-phase mass flow rate out of the tank. Most of the work about this problem has been undertaken in the context of the nuclear power industry, giving rise to the well known HEM, and Moody and Fauske models for example. As a consequence, a striking feature of the literature is the large amount of papers delicated to experiments with water, and the very small number of works devoted to other fluids, essentially refrigerants. However Process Industry is mainly concerned with other fluids. Moreover, because of the differences between each experimental setup and protocol, results from different labs can seldom be compared one with the other.

In this context we developed the so-called GAZLIQ Program (supported by three french industrial groups: ELF, GESIP and SNPE-INGENIERIE). The aim of this program is to extend the experimental data base using several fluids essentially different one from the other with one single experimental setup and then to validate the available models against this data base.

Experimental setup:

It consists of a stainless steel jacketed upstream column (0.23 m^3, 5 MPa, 4.5 m high) connected to the test section (where the critical two-phase flow under study occurs) via a 3" ball valve. As the test section we use an horizontal tube 0.5 m in length, 4, 6 or 8 mm inner diameter provided with a rounded entrance. Two control loops allow us to monitor both temperature (and then vapour pressure) and total pressure (by means of nitrogen input).

We measure both mass flow rate in the test section (by means of hydrostatic pressure variations in the upstream column) and pressure profile in the test section as a function of the thermodynamic conditions of the fluid in the tank (total pressure and subcooling). The setup is equipped with a 4 m^3 downstream tank; this avoids releasing the fluids into the atmosphere and allows subsequent recycling of them.

The difficulty with this experiment is the sensitivity of the mass flow to even a small extent of subcooling. For this reason we carefully insulated all the column, so as to obtain a homogeneous temperature in it within ±0.1°C accuracy. We also designed a cell for measuring the subcooling within ±1 kPa accuracy. This setup can work even if the vapour pressure of the fluid is not known from tables.

Results:

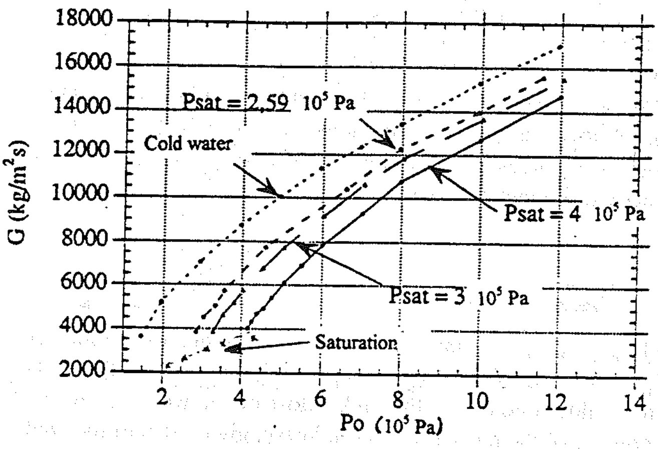

Figure 1: Mass flow rate of water against upstream total pressure (pipe: L = .5 m, ϕ = 4 mm)

As an example figure 1 shows mass flow rate of water against total pressure in the column for different temperatures and hence different vapour pressures. Each curve corresponds to one temperature (and hence one vapour pressure) with a varying total pressure. As a reference we give also the curve obtained for cold water. Similar results were obtained using the same experimental apparatus with R11, methanol, ethylacetate and butane. This means that results were obtained with always the same initial and geometrical conditions. Only the thermodynamical and transport properties changed.

Discussion:

When a loss of containment event occurs the contents of the tank can be subcooled by several bars (due for example to sunshine) as observed by Nyren et al (1983). The preceeding results show that the mass flow rate can then be multiplied by a factor of 2 to 4 compared to the saturation condition. So it is very important to be able to model the mass flow rate in this case. From the physical point of view, we have to discern between two cases: low subcooling and high subcooling case, say less and more than .2 MPa overpressure.

In the high subcooling case Henry et al (1970), Collins (1980) or Leung et al. (1988) suggest using an isentropic Bernoulli type equation: $G = \sqrt{2\rho_{l_0}\left(P_0 - P_{sat}(T_0)\right)}$

In our case this relation leads to an over estimation of the mass flow rate of up to 100%! A better estimation can be obtained by simply taking into account wall shear stresses as proposed by Lackmé (1980): $G = \sqrt{\dfrac{2\rho_{l_0}\left(P_0 - P_{sat}(T_0)\right)}{1+\dfrac{\lambda L}{D}}}$

Then the estimation is very good (within ±20%, see figure 2), for all of the fluids. This is because in the high subcooling case flow is liquid almost down to the exit and friction effects have necessarily to be taken into account for tubes with a high L/D ratio. These results show than Collins was right when he suggested that the homogeneous equilibrium model (HEM) could be extended even to initially subcooled fluids.

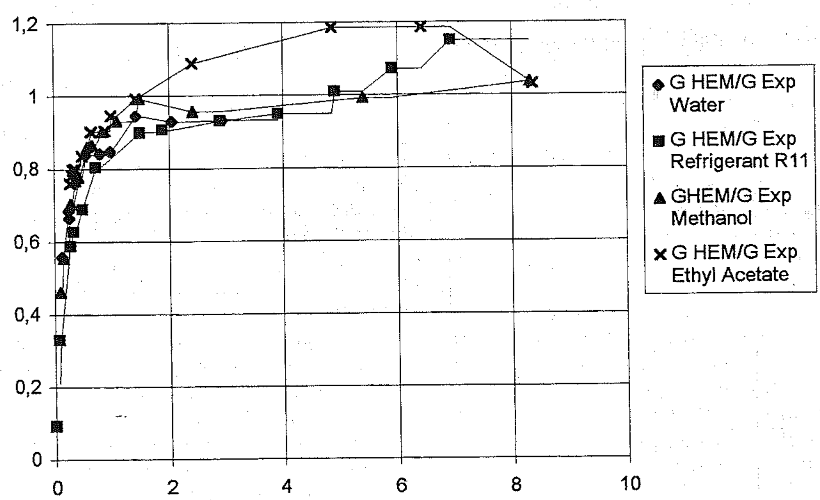

Figure 2: Extended HEM to experimental mass flow rate ratio against overpressure (10^5 Pa)

In the low subcooling cas modelling is more difficult because the two-phase region with non-equilibrium effects has to be taken into account. Both the Delayed Equilibrium Model (DEM) from Feburie et al. (1993) and the Homogeneous Relaxation Model (HRM) proposed by Bolle et al. (1995) give good estimates of the mass flow rate (within ±30% accuracy) for all of the tested fluids even at very low subcooling.

The fact that good estimates for the mass flow rate of five very different fluids can be obtained from models (extended HEM for high subcooling conditions, DEM or HRM for low subcooling

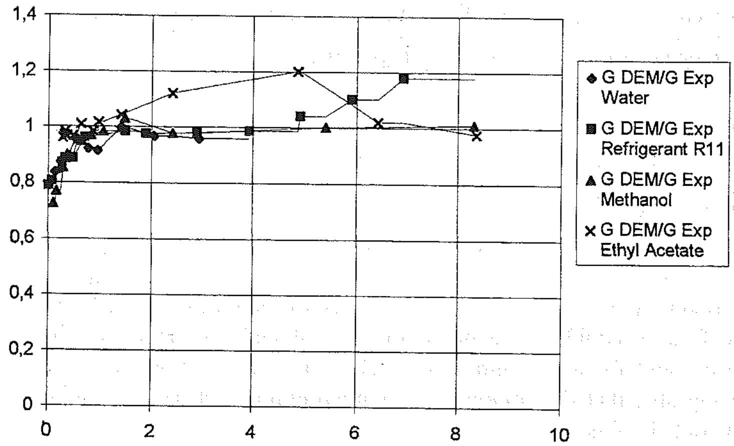

Figure 3: DEM to experimental mass flow rate ratio against overpressure (10^5 Pa)

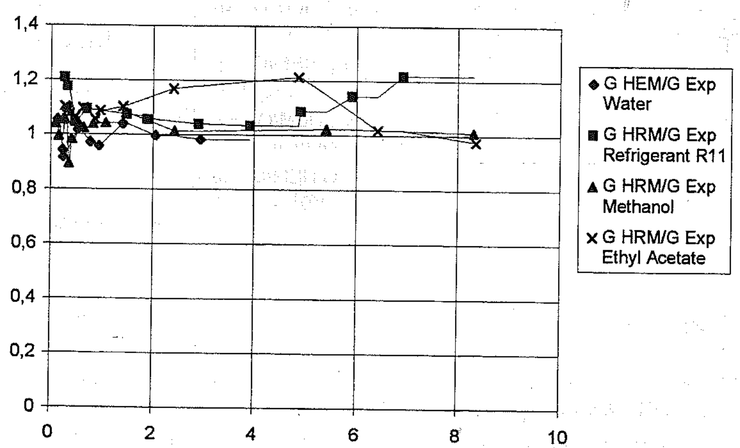

Figure 4: HRM to experimental mass flow rate ratio against overpressure (10^5 Pa)

conditions) seems to indicate that these models take good account of all the main phenomena occuring in initially subcooled critical two-phase flows.

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